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Additional results from the first dedicated search for neutron–mirror–neutron oscillations

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The existence of a mirror world holding a copy of our ordinary particle spectrum could lead to oscillations between the neutron (n) and its mirror partner (n′). Such oscillations could manifest themselves in storage experiments with ultracold neutrons whose storage lifetime would depend on the applied magnetic field. Here, extended details and measurements from the first dedicated experimental search for *nn′* oscillations published in [G. Ban, K. Bodek, M. Daum, R. Henneck, S. Heule, M. Kasprzak, N. Khomutov, K. Kirch, S. Kistryn, A. Knecht, P. Knowles, M. Kuźniak, T. Lefort, A. Mtchedlishvili, O. Naviliat-Cuncic, C. Plonka, G. Quéméner, M. Rebetez, D. Rebreyend, S. Roccia, G. Rogel, M. Tur, A. Weis, J. Zejma, G. Zsigmond, Direct experimental limit on neutron mirror–neutron oscillations, Phys. Rev. Lett. 99 (2007) 161603] will be presented, focussing on a possible dependence of the UCN counts on the magnetic field and its direction. However, at present no significant change in the averaged UCN counts with respect to the applied magnetic field has been found.

1. Introduction

The idea of a mirror world whose existence would restore parity symmetry has obtained considerable interest since the 1950s following its first proposal by Lee and Yang [2]. Since then, the concept has been significantly expanded in the work of Kobzarev et al. [3] and reconciled with the Standard Model of particle physics in Ref. [4]. A more detailed description of this development can be found in Ref. [5].

The mirror world would hold a complete copy of the particle spectrum of our ordinary world. Matter and mirror matter would interact only via gravity thus providing a viable Dark Matter candidate [6–12]. Additionally, other (new) interactions could lead to minute mixings between neutral particles such as neutrinos, pions, kaons, photons, or neutrons and hence to oscillations between the two corresponding degenerate partners.

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Up to this experiment, only the photon case had been directly probed by searching for invisible decays of positronium [13].

For neutrons, a crude limit on the oscillation time between neutron (n) and mirror neutron (n′) of $\tau_{nn'} \geq 1$ s was derived in Ref. [14] based on the neutron–antineutron oscillation experiment [15]. Our collaboration conducted the first dedicated search for nn′ oscillations using the storage of ultracold neutrons (UCN, see Ref. [16] for a discussion of experimental techniques sensitive to nn′ oscillations). The experiment and analysis are described in detail in Ref. [1], and the results gave a two order of magnitude improvement over the crude limit:

$$\tau_{nn'} \geq 103\ \text{s (95\% CL)}. \tag{1}$$

In the meantime, this limit was improved by another factor of 4: $\tau_{nn'} \geq 414$ s (90% CL) [17]. Here, we discuss the possible dependence of the UCN counts on the applied magnetic field strength and direction. We present the results of an extended check using data taken six months after the data published in Ref. [1].

2. Apparatus

The apparatus used for the measurements in Ref. [1] and the data presented here are the same one used to set the best upper limit on the electric dipole moment of the neutron (nEDM) [18] and which has kindly been lent to us by the RAL/Sussex/ILL collaboration.

In contrast to the normal operation during nEDM searches, the UCN polarising foil in the fill line had been removed, thus allowing unpolarised UCNs to fill the storage chamber. After 40 s of filling, the storage chamber shutter was closed and the UCNs were kept in the chamber (made of diamond-like carbon and deuterated polystyrene) for a given storage time. Finally, the shutter was opened and the remaining UCNs counted in a ^{3}He-detector during 40 s. The two main components for the conducted measurements were (i) the four layer magnetic shield permitting measurements at magnetic fields small enough to be negligible and (ii) the magnetic field coil allowing for measurements at well defined magnetic field (B field) values.

3. Measurements and results

The final results of the averaged UCN counts were presented in Table 1 of Ref. [1] and are reproduced here in Fig. 1. The measurements were done for three different storage times: 50 s (a), 100 s, and 175 s. Some further measurements with 50 s—depicted with (b)—were made to clarify an unexpected deviation. In Fig. 1, the averaged UCN counts for the different storage times and for B field up (positive B field value on the graph's horizontal axis), B field down (negative B field value) and zero field (demagnetised four layer magnetic shield, $B \leq 50$ nT) are shown normalised to the counts at zero field. Three of the four data sets show a linear tendency with increasing B field value. Shown are also two fits to the data with the fitting results given in Table 1. Firstly, a constant fit giving an acceptable χ^2 yields a value which is consistent with 1 to within 1.3σ and secondly, a linear fit with an excellent χ^2 results in a slope deviating from 0 by 2.3σ. In the analysis of Ref. [1], it was assumed that the direction of the applied magnetic field did not influence the nn′ oscillations so any applied magnetic field only suppresses the nn′ oscillation mechanism. Therefore, the counts for B field up and down were averaged and only the combined result was used in the analysis resulting in the limit on the oscillation time given in Eq. (1).

To check if the UCN counts depended linearly on the applied B field, further measurements were made six months after the original data taking. Such a dependence would, of course, also be a systematic effect for the experiment searching for the nEDM, the original purpose of the apparatus (see Section 2). The sequence of measurements, all conducted at 50 s storage time, was as follows: During the first 6 h, the field was regularly changed (roughly every 30 min) between $\pm 7\,\mu$T and zero field. For the next 2 h, the field was changed between $\pm 14\,\mu$T followed by a 6 h run over night at $+14\,\mu$T (thereby acquiring the most statistics for that specific field configuration). The next day, the influence of some permanent magnets outside the magnetic shield was checked. Such magnets were used during the nEDM measurements to magnetise the UCN polariser's iron foil in the UCN fill line. The foil itself was not present but the permanent magnets creating a field of about 0.1 T in the centre of the UCN guide were added. During 3 h with regularly changing between $\pm 7\,\mu$T and 2 h changing between $\pm 14\,\mu$T, no significant difference to the UCN count rate without magnets was observed.

The overall count histogram was fitted with a Gaussian distribution yielding a width of $\sigma = 211 \pm 11$. The width expected from statistics is $\sqrt{\mu} = 213$, in perfect agreement with the fitted result. The counts for the different field configurations were thus statistically averaged and are shown in Fig. 2 with the results of the fitting procedures in Table 2. The fits to the full data set do not show a significant deviation from a constant. The linear fit shows a larger χ^2 per degree of freedom and the fitted linear parameter is consistent with 0 within 1σ. In order to compare with the fits of Fig. 1, a constant and a linear fit were also made for the three data points between -7 and $+7\,\mu$T. As in Fig. 1, there is a slight linear tendency with a resulting slope deviating from 0 by 1.9σ. The slope, however, has changed its sign with respect to the above result.

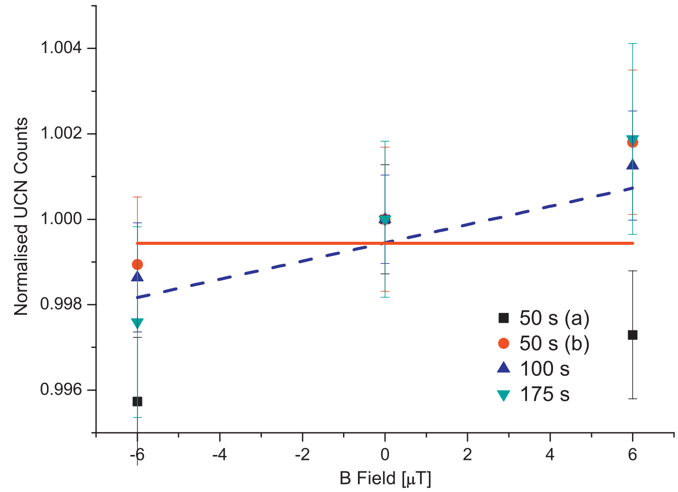

Fig. 1. (Colour online) Averaged UCN counts of Table 1 in Ref. [1] normalised to the counts at zero field as a function of the B field at four different storage times. Both a constant and a linear fit to the data are shown for which the parameters are given in Table 1. For more details, see text.

Table 1
Results of the fits with the function $f(x) = C_0 + C_1 x$ to the data presented in Fig. 1.

	Constant	Linear
χ^2/DoF	15.2/11	9.9/10
p-Value (%)	17	45
C_0	0.9994 ± 0.0004	0.9995 ± 0.0004
C_1 (1/µT)	–	$(2.1 \pm 0.9) \times 10^{-4}$

The p-value is the probability of obtaining an equal or higher χ^2.

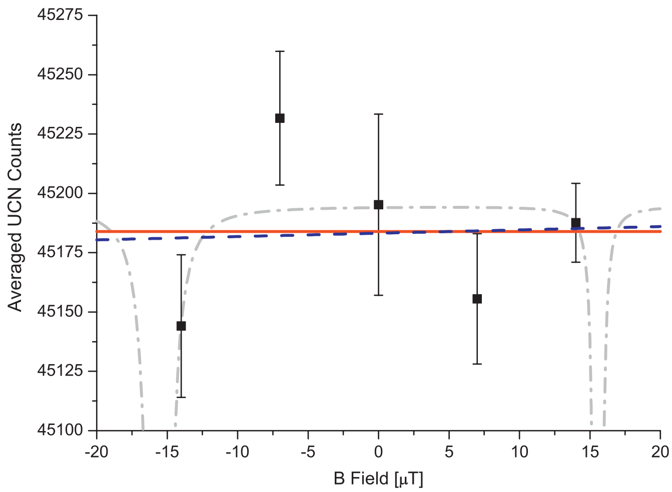

Fig. 2. (Colour online) Averaged UCN counts for 50 s storage time as a function of B field direction and strength. As in Fig. 1, a constant and a linear fit to the data are shown. In addition, a fit using the formalism derived in Ref. [19] is given. The fit parameters can be found in Table 2. Details in text.

Table 2
Results of the fits with the function $f(x) = C_0 + C_1 x$ and the model put forward in Ref. [19] to the data presented in Fig. 2.

	Constant	Linear	Model [19]
(i)			
χ^2/DoF	5.8/4	5.8/3	3.9/1
p-Value (%)	21	12	5
C_0	$45\,184 \pm 11$	$45\,183 \pm 12$	$N = 45\,195$
C_1 (1/μT)	–	0.1 ± 1.1	$B' = 15.6\,\mu\text{T}$
			$\beta = 138^\circ$
			$\tau_{nn'} = 10.5\,\text{s}$
(ii)			
χ^2/DoF	3.8/2	0.002/1	
p-Value (%)	15	97	
C_0	$45\,193 \pm 17$	$45\,194 \pm 17$	
C_1 (1/μT)	–	-5.4 ± 2.8	

(i) denotes the fits to the full data set, whereas for (ii) only the three data points between -7 and $+7\,\mu\text{T}$ were fitted. The p-value is the probability of obtaining an equal or higher χ^2.

4. Discussion

The main motivation behind the data taking presented in Fig. 2 was to check on the suggestion of a linear dependence observed in Fig. 1 by extending the range of the applied magnetic field.

In the meantime, Berezhiani derived in Ref. [19] the formalism of nn′ oscillations in the presence of mirror magnetic fields. In that context, the nn′ oscillation mechanism depends not only on the applied magnetic field strength B and oscillation time $\tau_{nn'}$, but also on the strength of the mirror magnetic field B' and the angle β between the mirror magnetic field and the "up"-direction of the ordinary magnetic field. Moreover, the angle β might change with time depending on the origin of the mirror magnetic field. For mirror magnetic fields originating from outside of Earth, this typically leads to daily modulated signals.

As neither the data set of Ref. [1] nor the present one cover several full 24 h cycles, we cannot extract reliable conclusions on a possible time dependence of the UCN counts. We assumed the absence of such a modulation and averaged the UCN counts.

For completeness, we show in Fig. 2 a best fit of the model derived in Ref. [19] to our data. The resulting parameters can be found in Table 2. In addition to the parameters described above, a normalisation parameter N was required. The position of the resonance is determined by the strength of the mirror magnetic field B', the width by the parameters β (for perfectly aligned ordinary and mirror magnetic field there is only one resonance present) and $\tau_{nn'}$, and the depth of the resonance by $\tau_{nn'}$. With the majority of the available parameter space still open and allowing for basically any combination of parameters, the extraction of meaningful limits is not possible. Meanwhile, additional data have been collected and their analysis can be found in Ref. [20].

5. Conclusions

In this paper, more details on the first dedicated search for nn′ oscillations published in Ref. [1] have been presented focussing on a possible dependence of UCN counts on the applied magnetic field and its direction. New data from an extended remeasurement six months after the original data taking has been shown. So far, no significant change in the averaged UCN counts with respect to the applied magnetic field has emerged.

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